Pressure Vessel Design Concepts for Planetary Probe Missions

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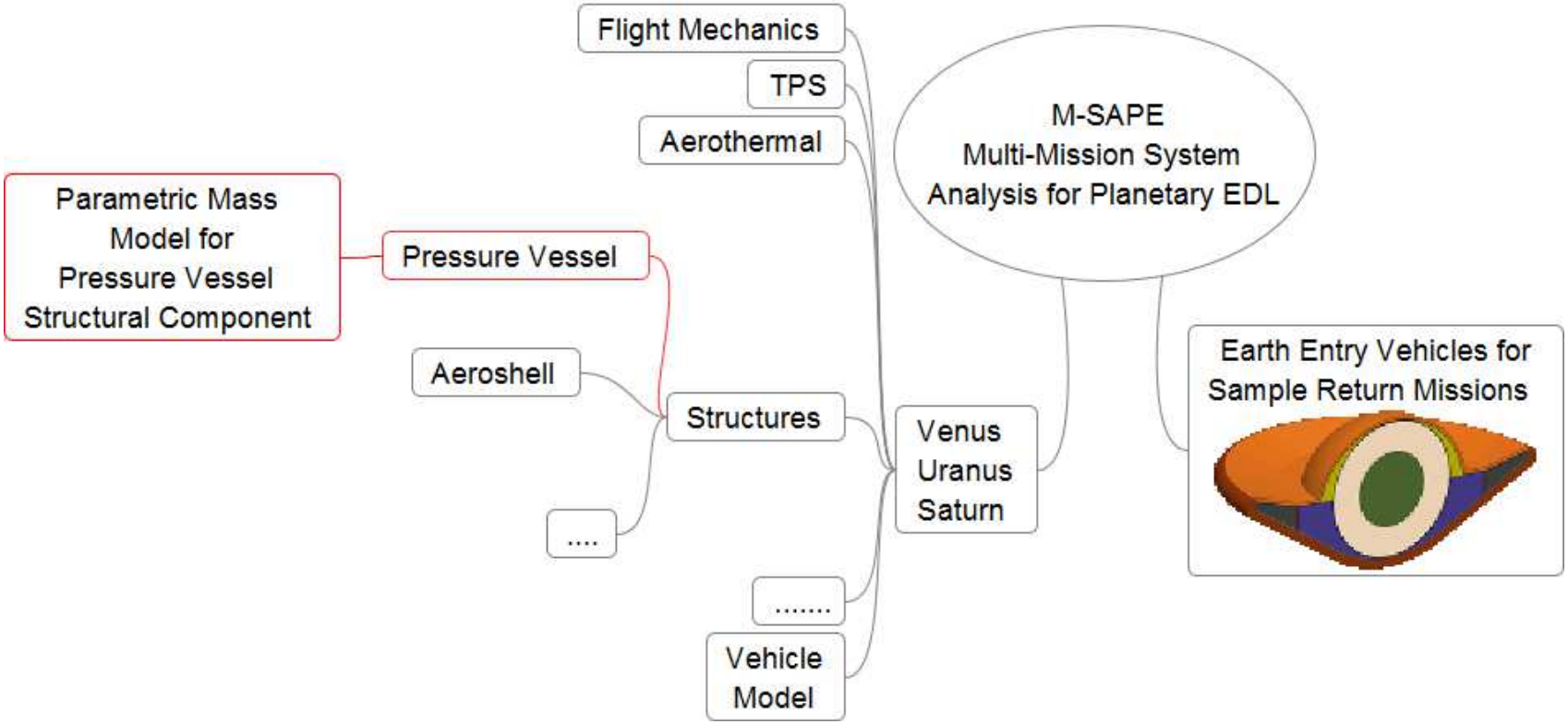
Multi-Mission System Analysis for Planetary EDL (M-SAPE)



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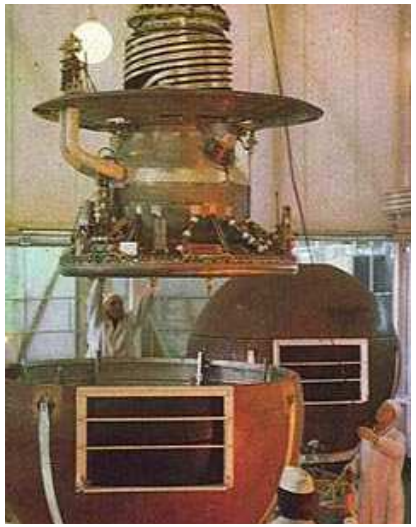
Motivation

- Materials and systems for extreme environments have been identified by the Outer Planets Assessment Group (OPAG) as technology needs for future planetary probe missions [1-2]. One critical element of this system is the lightweight pressure vessel component suitable for missions in extreme environments, and this element is considered the highest priority for in situ exploration [2].
- Pauken et al. [3] provide an excellent overview of metallic and advanced composite material selections. They conclude that there is a potential for reducing the mass of a titanium baseline pressure vessel for a mission to a high pressure/temperature environment .
- Stackpoole and et al. [4] propose a nano-reinforced titanium concept as candidate material for pressure vessels. Samples processed by Stackpoole indicate that there is a potential for a lower mass alternative for pressure vessel materials with 10% mass reduction and more than 200% increase in higher specific modulus.

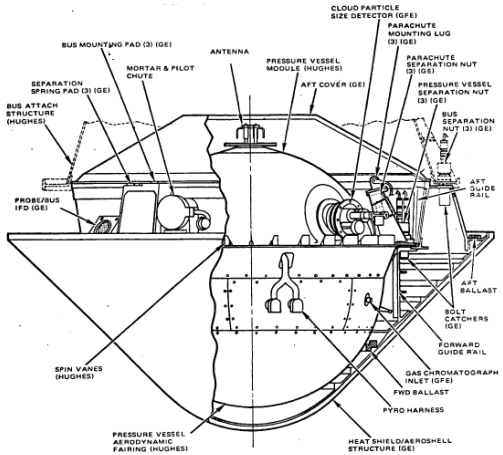
Extreme Environments

Venera Concept



Venera 4 Descent Module

Pioneer Venus (Large Probe)

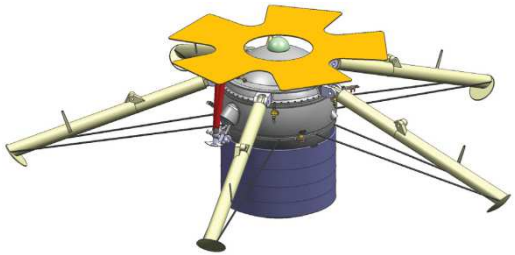


Galileo Descent

Jupiter Deep Entry Probe (Balint 2005)

NASA Flagship Mission to Venus

SAGE Lander



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Pioneer Venus

"Pioneer Venus Case Study in Spacecraft Design", Hughes Aircraft Company, AIAA, 1979

- All Pressure Vessels were essentially configured the same.
- Entry loads of 565 & 400 g's, for small and large probes.
- Titanium (6AL-4V) monocoque with solid beryllium shelves.
- Sized for the Venus surface condition (1400 psi & 920°F)
- Waffle pattern rib stiffened did not prove to be competitive
- Ports & windows (mechanical and thermal load paths)
- Factor of safety of 1.25 on pressure
- Knockdown factor, K (0.4-0.7, redesigned with 0.7)
- Design changed from externally insulated to internally insulated (K 0.7->0.5)

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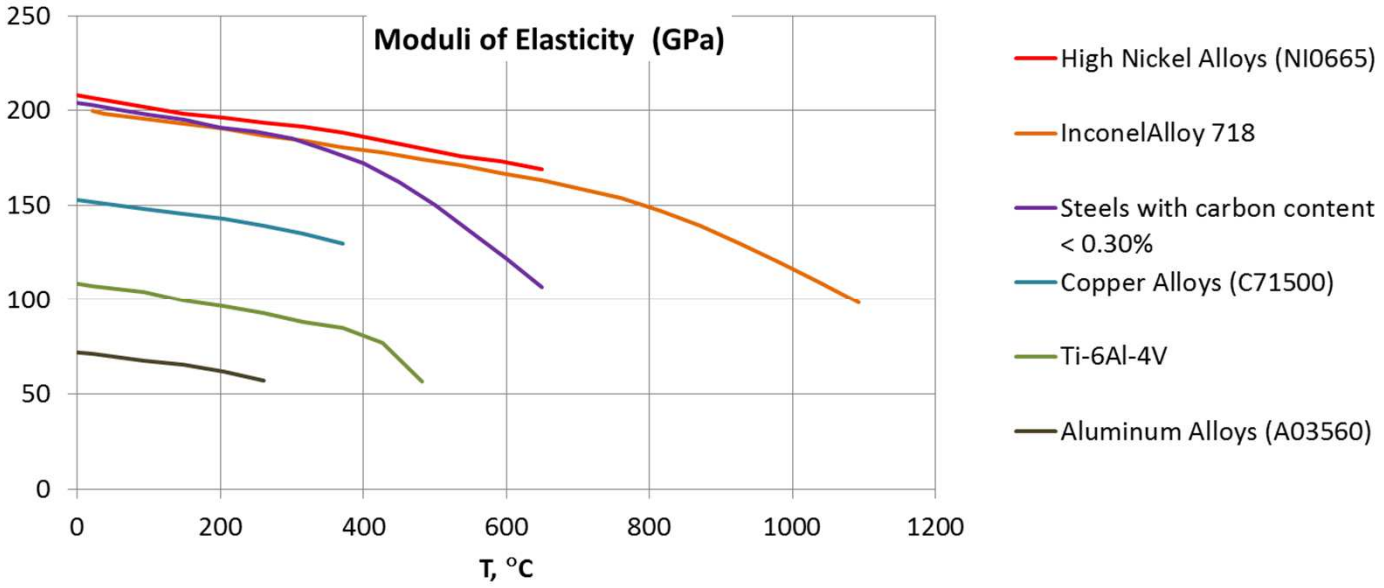
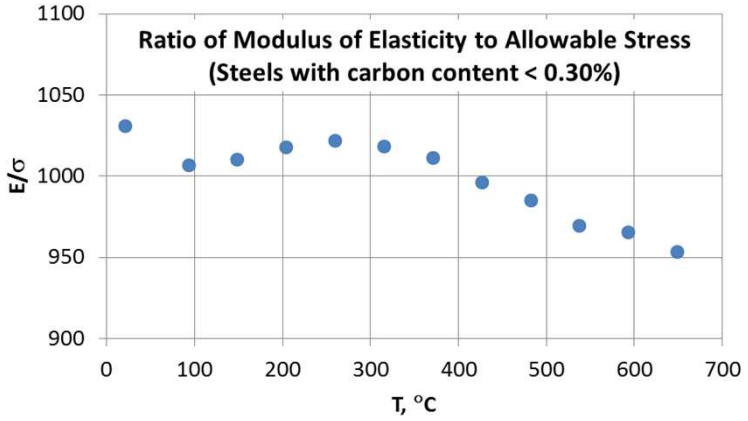
Material Selection

(Addenda to ASME 831.1-2007 & MIL-HDBK-5H-1998)



E/ρ(SI)	Materials
1.9E+07	High Nickel Alloys (NI0665)
2.1E+07	InconelAlloy 718
1.9E+07	Steels with carbon content < 0.30%
1.4E+07	Copper Alloys (C71500) @370C
1.7E+07	Titanium
2.1E+07	Aluminum Alloys (A03560) at 200C



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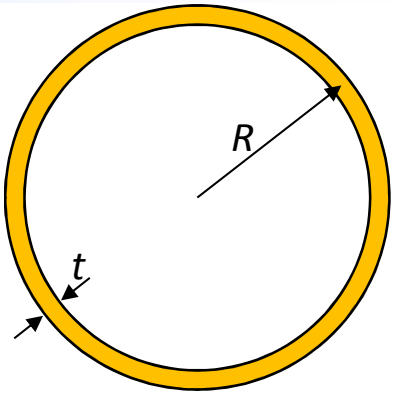
Parametric Mass Model

(External Pressure)



Roark's Formulas for Vessels with External Pressure:

$p = \frac{2}{\sqrt{3(1-\nu^2)}} E \left(\frac{t}{R}\right)^2$, for ideal case

$p = 0.365 E \left(\frac{t}{R}\right)^2$, recommended minimum p

$p = C E \left(\frac{t}{R}\right)^2$, (Eq. 1) C is a constant (either 0.365 or $\frac{2}{\sqrt{3(1-\nu^2)}}$)

Mass:

Mass = ϱ. volume = $\varrho . A . t$, (Eq. 2) ϱ is density, A surface area

Substitute t from Eq. 1 into Eq. 2 and rearrange terms

$$\text{Mass} = \frac{3}{\sqrt{C}} . \frac{4\pi}{3} R^3 \frac{\sqrt{p}}{\left(\frac{\sqrt{E}}{\varrho}\right)}$$

Environment

Material

Geometry

Vessel with Internal Pressure

$$\text{Mass} = \frac{3}{2} . \frac{4\pi}{3} R^3 \frac{p}{\left(\frac{\sigma}{\varrho}\right)}$$

σ maximum allowable stress

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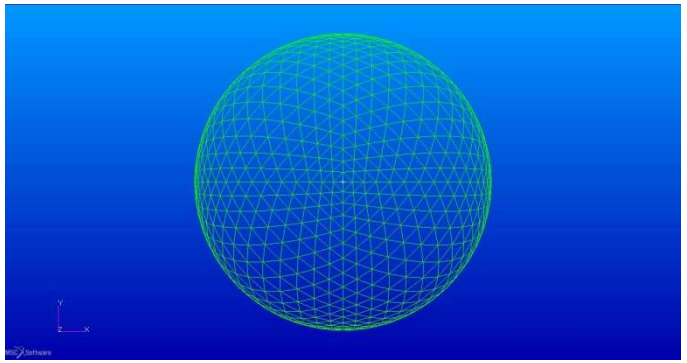
Parametric Mass Model (Cont.)

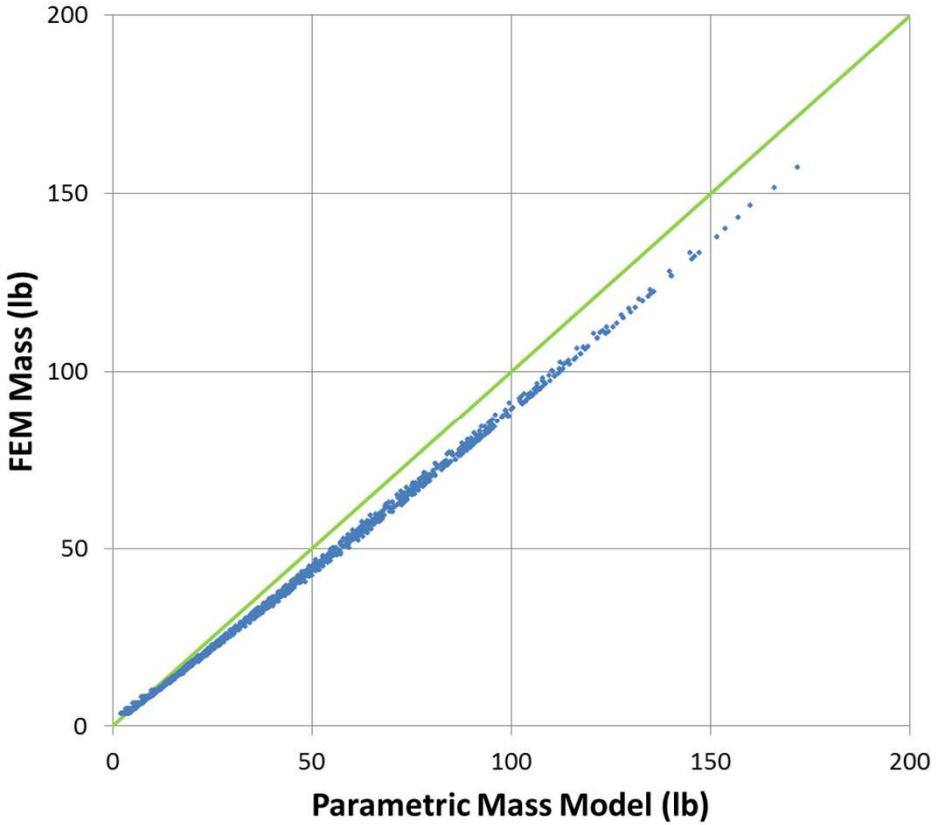


- Solution 200 of MSC.Nastran was used for all optimization
  - Originally three solutions (strength, buckling, and normal modes) were embedded under SOL 200
- Two Boundary conditions
  - External pressure over all surfaces
  - Displacement constraints on four grids, orthogonal to each other, to take out three translations and three rotations
- Objective function was set as the mass of the structure
- Optimization constraints…
  - Buckling: first buckling mode
  - Strength: Von Mises stress
  - Normal Modes: First frequency higher than 7 Hz – All solutions met the frequency constraints, thus this solution was eliminated to save CPU time

Parametric Mass Model (Cont.)

NASTRAN mass sizing

- **1573 cases**
  - **11 Ps [700-2100 psi]**
  - **13 Rs [6, 18]**
  - **11 Es [8.25E6-24.8E6 psi]**
- **Took ~7 hours on a 12-core computer**



$$\text{Parametric Mass} = \frac{3}{\sqrt{\frac{2}{\sqrt{3(1-\nu^2)}}}} \cdot \frac{4\pi}{3} R^3 \frac{\sqrt{p}}{\left(\frac{\sqrt{E}}{\varrho}\right)}$$

Parametric Mass Model (Cont.)

$$\text{Mass} = \frac{3}{\sqrt{\sqrt{\frac{2}{3(1-\nu^2)}}}} \cdot \frac{4\pi}{3} R^3 \frac{\sqrt{p*FS/K}}{\left(\frac{\sqrt{E}}{\varrho}\right)} \eta,$$

FS = Factor safety

K = Knockdown factor

η = Margin, MGA,….

Pioneer Venus

	Small Probe	Large Probe
Pressure (psi)	1400	1400
E (psi)	8.25E+06	8.25E+06
R (in)	9	14.6
FS	1.25	1.25
knock-down factor (K)	0.5	0.5
Margin, MGA, … (η)	1.3	1.3
ν	0.31	0.31
ρ (lb/in^3)	0.163	0.163
Parametric mass (lb)	**36.3**	**154.9**
Actual	**40.4**	**135.7**
Difference (%)	10%	-14%

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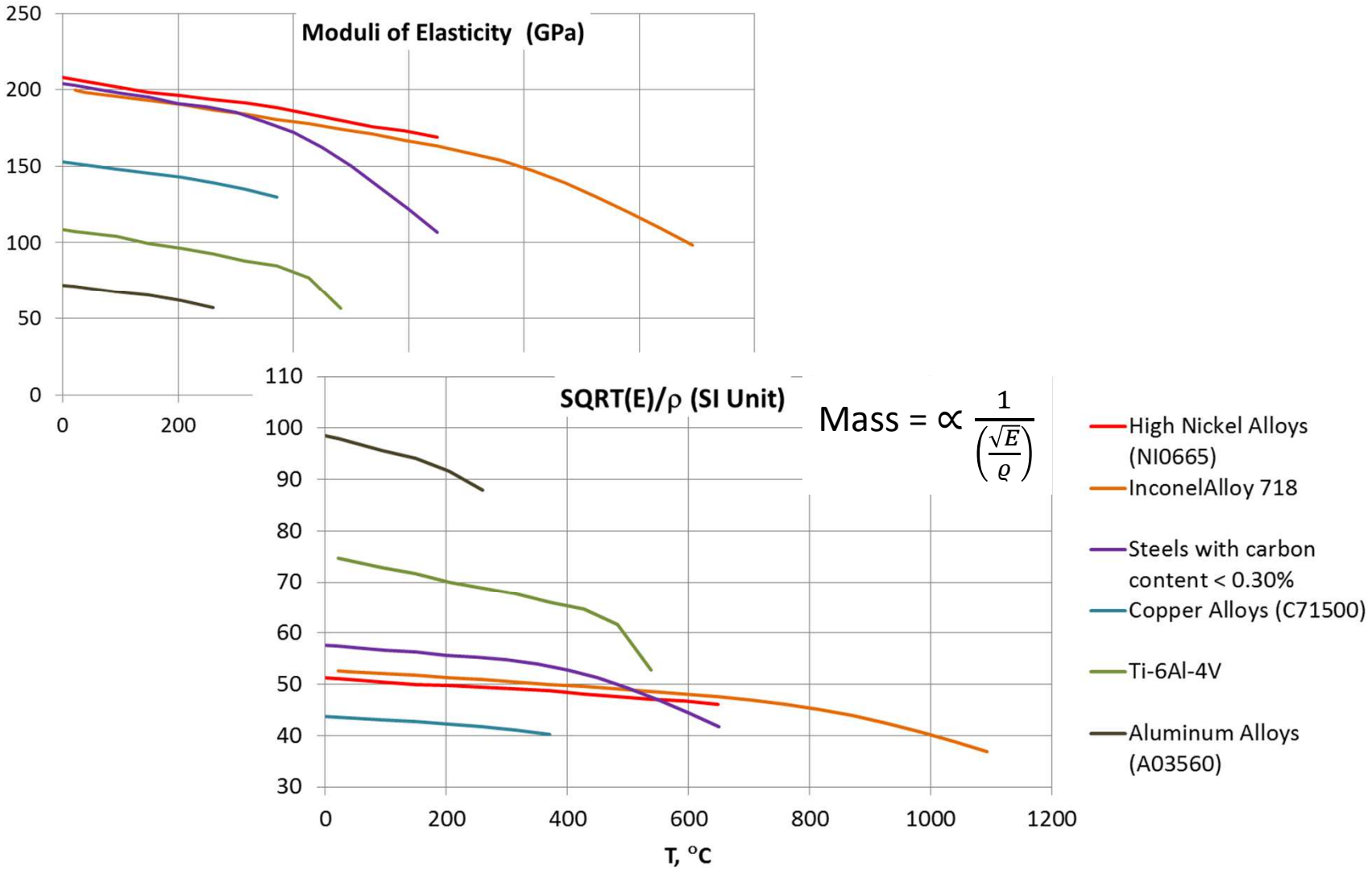
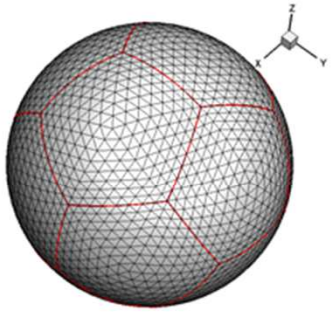
Parametric Mass Model (Cont.)

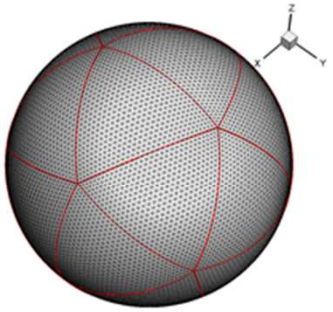


Ring Stiffened Pressure Vessel

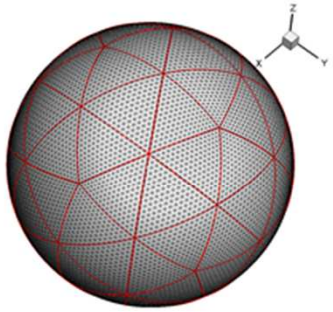
Dodecahedron



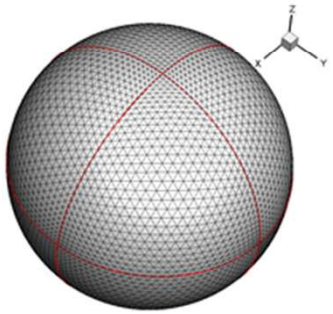
Icosahedron-A



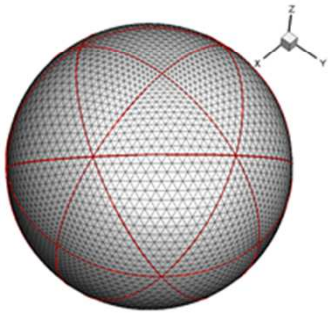
Icosahedron-B



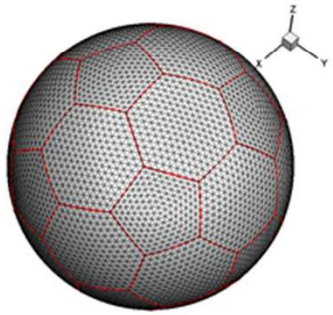
Octahedron-A



Octahedron-B



Truncated Icosahedron



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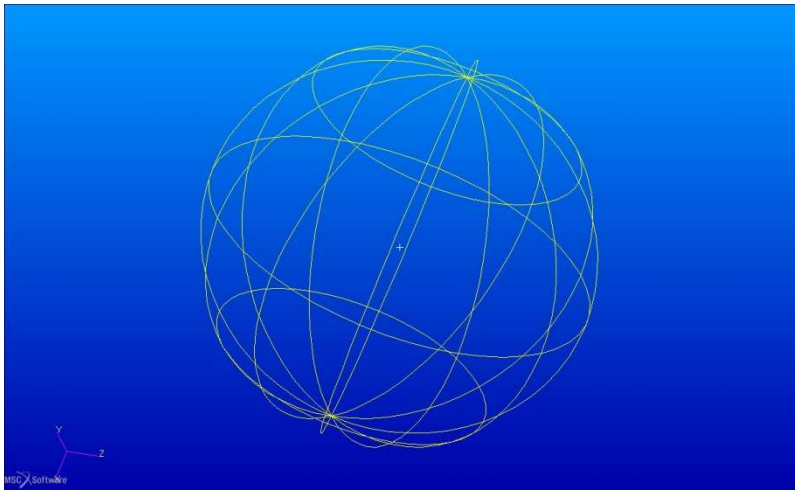
Ring Stiffened Pressure Vessel (Cont.)

- A sphere stiffened by a series of rings (bars) was also studied in optimization for strength and buckling.
  - Three sets of properties for optimization of bars were considered



- The optimization with additional bars took 92 iterations using 6:08 CPU-minutes versus 4 (with only shells) using 0:15 CPU-minutes.
- The weight decrease using the additional bars was only 1.7%
- Therefore, for this stage of the studies, the bars were removed.

Summary Remarks

- Developed a low fidelity mass model for pressure vessel that accurately represents optimized FE mass model.
- Identified appropriate figure of merit for material property suitable for pressure vessels design $\left(\sqrt{E}/\rho\right)$.
- Ring stiffened concept appears to have no significant advantage with current structural topology.

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References

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2) Beauchamp, P. M., "Technologies for Outer Planet Missions: A Companion to the Outer Planet Assessment Group (OPAG) Strategic Exploration White Paper,"
3) Pauken, M., Kolawa, E., Manv, R), Sokolowski, W., and Lewis, J., "Pressure Vessel Technology Development," International Planetary Probe Workshop, 2006.
4) Stackpoole, M., Srivastava, D., Fuentes, A., Cruden, B., and Arnold, J. O., "Nano-Reinforced Ti Composites as Candidate Pressure Vessel Materials for Deep Atmospheric Probes," 3rd International Planetary Probe Workshop, June 25 - July 1, 2005.
5) Ross, C. T. F., "Pressure Vessels Under External Pressure, Statics and Dynamics," Elsevier Applied Science, London, 1990
6) Balint, T. S., "Overview of Mission Architecture Options for Jupiter Deep Entry Probes," Presented at the Outer Planets Advisory Group Meeting, Boulder, Colorado June 9-10, 2005.
7) Anonymous, "Large and Small Probe Data Book," June 1976, Contract NAS2-8300, HS507-5164.
8) Dyson, R. W., Penswick, L. B., Burder, G. A., "Long-Lived Venus Lander Conceptual Design: How To Keep It Cool," AIAA-2009-4631.

Backup Slides

Pioneer Venus (Cont.)

"Pioneer Venus Case Study in Spacecraft Design", Hughes Aircraft Company, AIAA, 1979

TABLE 5-10. LARGE PROBE PRESSURE VESSEL TYPICAL TRADE STUDY RESULTS AND SHELL WEIGHT COMPARISONS

Construction	Material	Governing Mode of Failure	Shell Weight, lb	Anticipated Cost Factor	Development Risk
Monocoque	Ceramic (alumina)	Buckling (K = 0.4)	22.6	Low	High
	Beryllium	Compressive yield (even with K = 0.15)	22.0	High	Low
	Aluminum 7075-T73 Fcy = 52,000	Buckling (K = 0.4) σ = 46,000	29.4	Low	Low
	Titanium 6AL-4V Fcy = 112,000	Buckling (K = 0.4) σ = 58,000	36.9	Low	Low
	Steel (4340) Fcy = 210,000	Buckling (K = 0.4) σ = 80,000	50.2	Low	Low
Honeycomb sandwich	Titanium 6AL-4V	Simultaneous buckle and yield	18.3	High	High
	Aluminum 7075-T73	Simultaneous buckle and yield	25.6	High	High
	Steel (Inconel)	Simultaneous buckle and yield	26.5	High	High
External waffle stiffened	Titanium 6AL-4V	Simultaneous buckle and yield	27.4	High	Low

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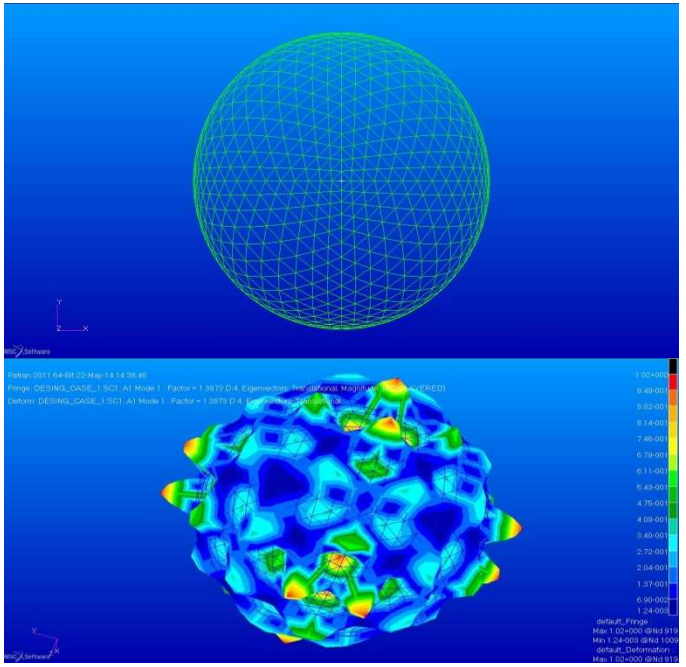
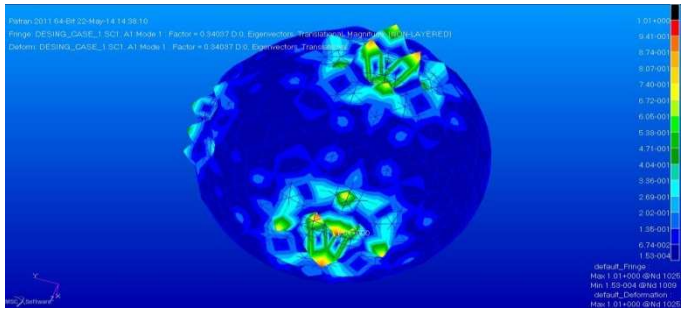
Parametric Mass Model (Finite Element Model)

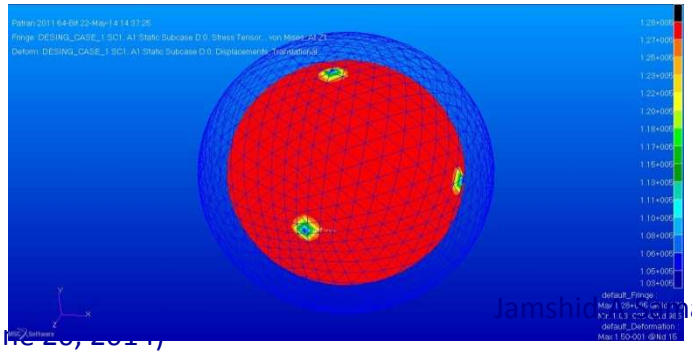
Titanium
R = 14.6 in
P = 1750 psi (nominal + 25%)
E = 8.25e6 psi (50% of E at room temperature)
σ=6.33e4 psi
Mass = 90.67 lbs (no margin or knockdown factor)

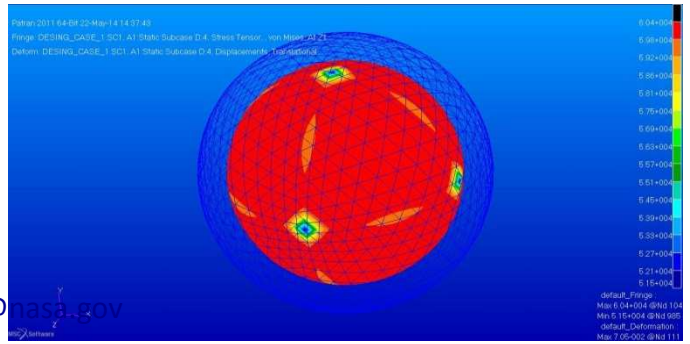




Un-optimized structure buckles in only a few local areas, and majority of its surface experiences low stresses, i.e. unused

Optimized structure buckles in more locations and more globally, and majority of its surface experiences equal to yield strength





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Pioneer Venus (Cont.)

(Ratio of Actual Buckling Pressure to Theoretical Buckling Pressure)

Knockdown Factor (Krenzke, AIAA J, Vol. 1, No. 12, 1963)

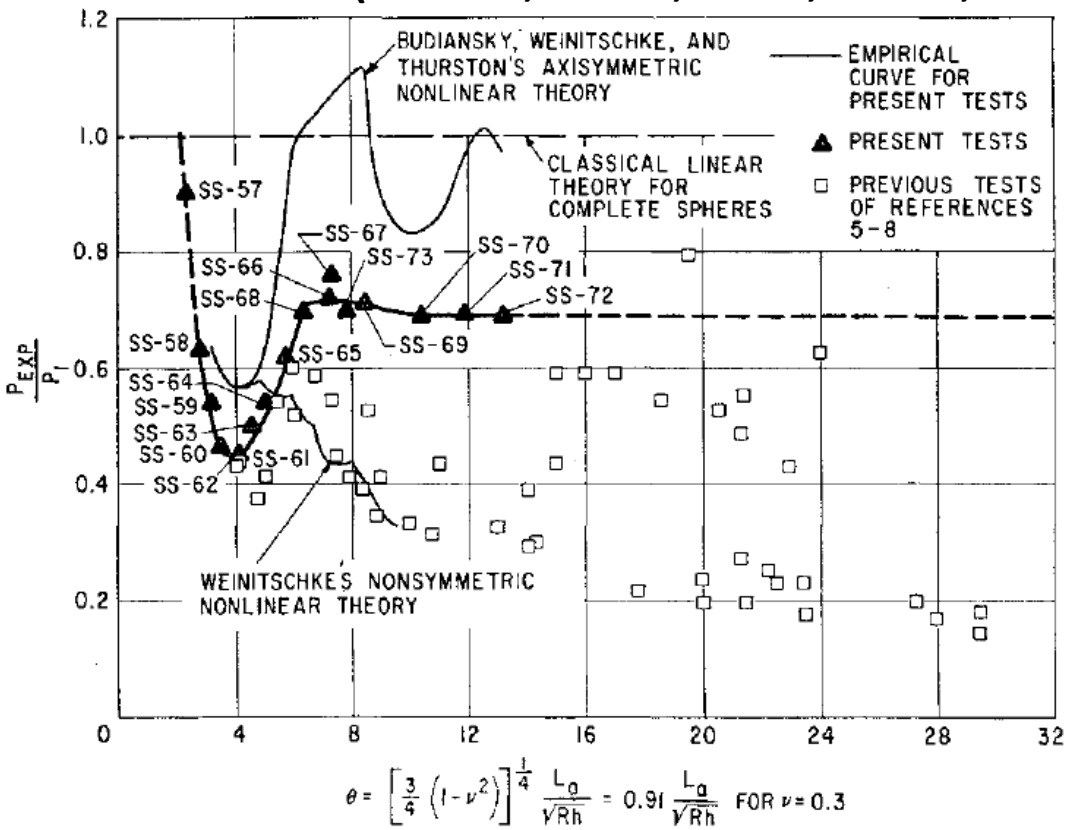

Fig. 1. Experimental elastic buckling data for shallow spherical shells with clamped edges.

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Pioneer Venus
(Data Book, 1976)

Large Probe **Small Probe**

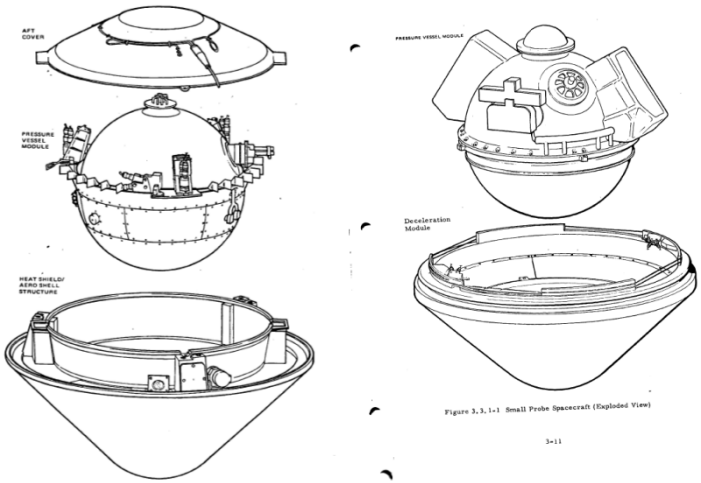

Figure 1.3.1-1 Large Probe Spacecraft (Exploded View)

1-12

Figure 3.3.1-1 Small Probe Spacecraft (Exploded View)

3-11

Large Probe	Small Probes	Pressure Vessel
29.2	18	Diameter, in
41 layer kapton	41 layer kapton	Internal
N2 gas, 8-20 psia	N2 gas & 4-30 psia	Internal
aluminized kapton blanket	aluminized kapton blanket	Internal insulation
Beryllium for high capacity heat sink	Beryllium for high capacity heat sink	Internal shelf
1	<3	Temperature rise during entry, F
135.66	40.37	Pressure Vessel Mass, lbs
AL ring-stiffened monocoque	Bonded to titanium	Bonding concept
1.25*1400 psia	1.25*1400 psia	Factor of Safety
922	922	Max operating
1.25 * max entry load	1.25 * max entry load	Entry load factor, Earth g's
-80 to 922	-80 to 922	Temperature fluxtuations, F

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